

ACCURACY OF STAR CLUSTER PARAMETERS FROM INTEGRATED *UBVRI* PHOTOMETRY

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Abstract. We study the capability of the *UBVRI* photometric system to quantify star clusters in terms of age, metallicity, and color excess by their integrated photometry. The well known age-metallicity-extinction degeneracy was analyzed for various parameter combinations, assuming different levels of photometric accuracy. We conclude that the *UBVRI* photometric system enables us to estimate star cluster parameters over a wide range, if the overall photometric accuracy is better than ~ 0.03 mag.

Key words: techniques: photometric methods – galaxies: star clusters

1. INTRODUCTION

We investigate the possibility to quantify star cluster parameters (age t , metallicity $[M/H]$ and color excess E_{B-V}) comparing their integrated color indices $U-V$, $B-V$, $V-R$ and $R-I$ with the simple stellar population (SSP) models. The purpose of this study is to evaluate the reliability of the derived parameters assuming different levels of photometric accuracy, and to identify parameter ranges susceptible to degeneracies.

For similar purposes various χ^2 minimization techniques have been used (e.g., Bik et al. 2003, Maíz-Apellániz 2004, de Grijs et al. 2005). The systematic uncertainties of quantified parameters, associated with the selection of photometric passbands, have been studied in detail by Anders et al. (2004). The importance of interstellar extinction and star cluster metallicity has been widely discussed based on various SSP models and parameter quantification techniques by de Grijs et al. (2005). These studies concentrated on a statistical analysis of the derived parameters for large samples of artificial or real star clusters.

In this study we have estimated the *UBVRI* photometric system capabilities to quantify star cluster parameters (age, metallicity and color excess) and analyzed their degeneracies at various photometry accuracy levels.

2. THE METHOD

We employed the PÉGASE (v. 2.0; Fioc and Rocca-Volmerange 1997) program package to compute SSP models ($U-V$, $B-V$, $V-R$ and $V-I$ color indices) of various ages and metallicities. The default PÉGASE parameters were applied, but the universal initial mass function (Kroupa 2002) was assumed. The reddened color indices were calculated as a function of color excess E_{B-V} , assuming the

standard extinction law (Cardelli, Clayton & Mathis 1989). The three-parameter SSP model grid was constructed at the following nodes: (1) 76 age (t) values from 1 Myr to 20 Gyr, with a constant step of $\log(t/\text{Myr}) = 0.05$, starting from $t = 6$ Myr (for younger ages grid nodes are located at 1, 2, 3, 4, 5 Myr); (2) 31 metallicity $[M/H]$ values from -2.3 to $+0.7$, with a step of 0.1 dex; (3) 201 color excess E_{B-V} values from 0.0 to 2.0, with a step of 0.01 (473 556 models in total).

The sample of 54 SSP models was selected from the model grid for further analysis as the test star clusters ($t = 20, 50, 100, 200, 500$ Myr and 1, 2, 5, 10 Gyr; $[M/H] = 0.0, -0.7, -1.7$; $E_{B-V} = 0.1, 1.0$). The first color excess value was chosen to represent a typical foreground Milky Way extinction, inherent to extragalactic objects, and the second – substantially obscured star clusters in the spiral galaxy disks.

A star cluster parameter quantification code, using a technique similar to the one developed for star quantification (Vansevičius & Bridžius 1994), was implemented in the environment of data analysis and graphing software package “Origin”¹. The parameter quantification is based on a comparison of the observed color indices of star clusters with those of the SSP models from the model grid. For this purpose we use the quantification criterion δ , which is calculated according to the formula:

$$\delta = \sqrt{\frac{\sum_{i=1}^n W_i (CI_i^{\text{obs}} - CI_i^{\text{mod}})^2}{\sum_{i=1}^n W_i}}, \quad (1)$$

where CI_i^{obs} stands for the observed star cluster color indices $U-V$, $B-V$, $V-R$ and $V-I$; CI_i^{mod} – the corresponding color indices of SSP models from the grid; n – the number of color indices used; W_i – the weights of the observed color indices. In the present study CI_i^{obs} represents color indices ($n = 4$) of the test star clusters, and weights assigned to color indices are equal ($W_i = 1$). The quantification criterion δ mimics the effect of photometric accuracy. In general, it represents average observation errors of color indices. Therefore, we use δ to study star cluster parameter degeneracies and, by setting different δ_{max} thresholds, determine parameters and estimate their accuracy for a corresponding photometric error budget.

The test star cluster colors are compared with the colors of all SSP models from the model grid and δ is calculated at each grid node. Then the test star cluster parameters (t , $[M/H]$ and E_{B-V}) are calculated as the SSP model parameter weighted averages, using only those models, which have δ lower than the applied threshold ($\delta \leq \delta_{\text{max}}$). We use five δ_{max} values (0.01–0.05 mag, with a step of 0.01 mag) and provide the quantification results as well as their standard deviations in Figures 1 and 2 for color excess values $E_{B-V} = 0.1$ and 1.0, respectively. The weights for parameter averaging and calculation of standard deviations were assigned to 1 and to $(10^{-4}/\delta^2)$ for the SSP models with $\delta \leq 0.01$ and $\delta > 0.01$, respectively.

The well known age-metallicity-extinction degeneracy makes the procedure described above not a trivial task, because of a few possible isolated $\delta \leq \delta_{\text{max}}$ “islands” in the parameter space. To overcome this problem we have chosen to select interactively a proper “island” for calculations of the parameters and their standard deviations. In reality such an improvement of the blind quantification

¹ “OriginLab Corporation”.

procedure could be based on multi-band star cluster environment images or other *a priori* information, e.g., metallicity estimated by spectroscopic methods. Therefore, to calculate the weighted averages of parameters and their standard deviations we used only the SSP models, which reside in a single selected “island”, satisfying the $\delta \leq \delta_{\max}$ criterion. This procedure excludes the models located in secondary δ minima, which arise due to parameter degeneracies. For purposes of the present study, boundaries of a continuous $\delta \leq \delta_{\max}$ “island” were determined by starting the search from the global δ minimum, i.e., from the position of the test star cluster under consideration in the SSP model grid. The parameter quantification maps for some characteristic test star clusters are shown in Figures 3–8.

3. RESULTS

The summary of the parameter quantification results of the 54 test star clusters is provided in Figures 1 and 2. In each panel the differences of parameters (determined minus true) are shown in groups of five filled circles (centered at their true age on t -axis), corresponding to the quantification criterion values of $\delta \leq 0.01 - 0.05$ mag, with a step of 0.01 mag (plotted from left to right). Error bars indicate standard deviations of the determined parameters and characterize sizes of the $\delta \leq \delta_{\max}$ “islands” in the parameter space. Note that higher metallicity (Figure 1) and larger extinction (Figure 2) make quantification procedure less accurate.

The parameter quantification maps of the representative star clusters of age $t = 50$ Myr, 500 Myr and 5 Gyr are displayed in Figures 3–8; different shades of gray represent $\delta \leq 0.01, 0.03$ and 0.05 mag (from the darkest to the lightest). The analysis of parameter quantification map patterns reveals, that the test star clusters can be subdivided into three broad age groups according to the shape of the age-metallicity degeneracy: (1) younger than ~ 100 Myr (Figures 3 and 4); (2) older than ~ 100 Myr and younger than ~ 1 Gyr (Figures 5–6); (3) older than ~ 1 Gyr (Figures 7–8). Note, however, that the age-extinction maps are much more regular, than the age-metallicity maps, and the shape of δ “islands” gradually changes from the youngest to the oldest cluster ages. In general, the parameter degeneracies seen in Figures 3–8 are mainly preconditioned by the properties of the *UBVRI* photometric system itself, and should not depend strongly on the PÉGASE SSP models used for the construction of the model grid.

The ultraviolet (UV) and infrared (*JHK*) passbands are known to be helpful for breaking the age-metallicity degeneracy, see, e.g., de Grijs et al. (2003). However, the accuracy of the UV and *JHK* photometry is usually lower than the accuracy, which can be achieved in *UBVRI* bands. Therefore, the information on metallicity – at least a rough estimate from spectroscopy – is of high importance for improving the accuracy of the quantification procedure. Even a “realistic” assumption, used in various star cluster studies (e.g., a study of the M51 galaxy by Bik et al. 2003), helps to constrain cluster ages.

We conclude that the *UBVRI* photometric system enables us to estimate star cluster parameters over a wide range, if the overall accuracy of color indices is better than ~ 0.03 mag.

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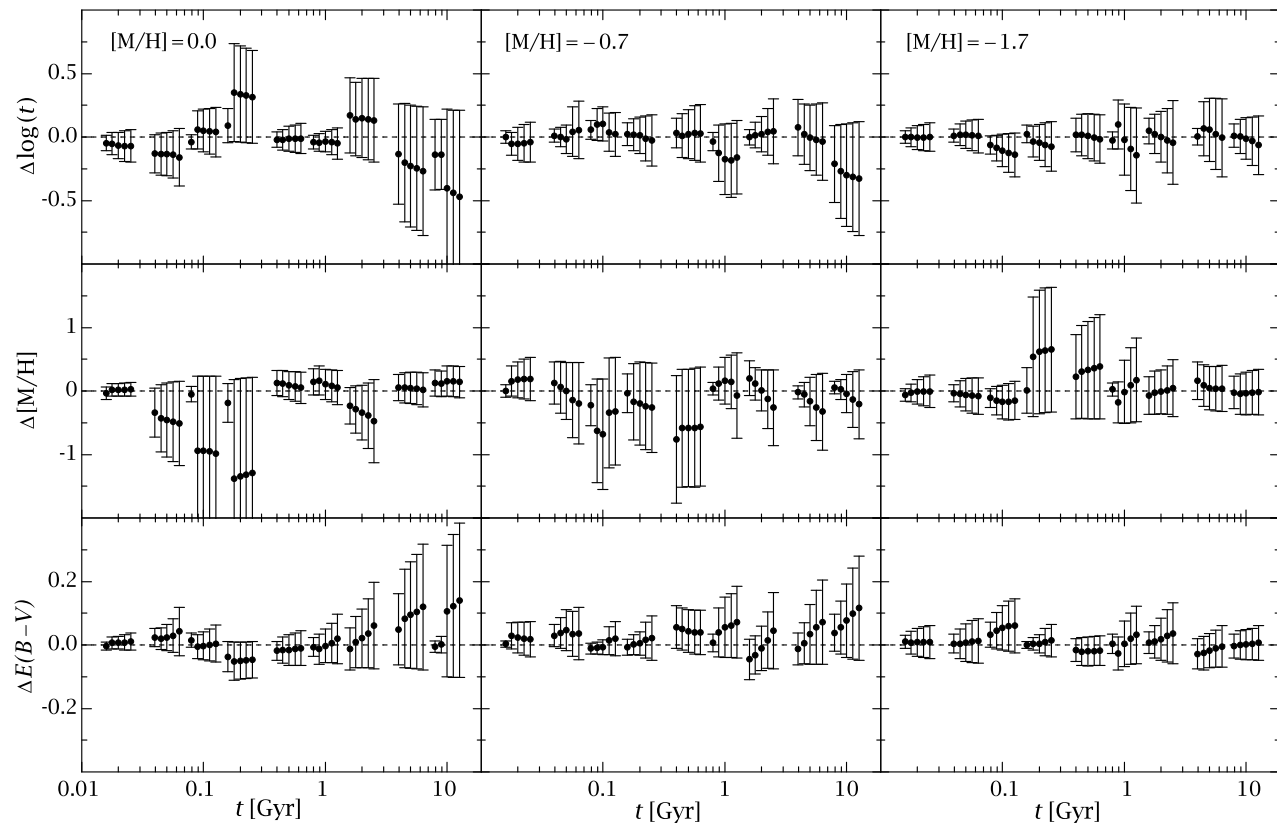


Fig. 1. Summarized test star cluster parameter quantification results for the case of color excess $E_{B-V} = 0.1$. Different metallicity ($[M/H] = 0.0, -0.7, -1.7$) cases are shown in the left, middle and right panels, respectively. Differences of the parameters (determined minus true) are shown in groups of five filled circles, centered at the true test star cluster ages; within a group from left to right the circles correspond to the quantification results derived at $\delta_{\max} = 0.01\text{--}0.05$ mag, with a step of 0.01 mag. Error bars indicate standard deviations of the derived parameters.

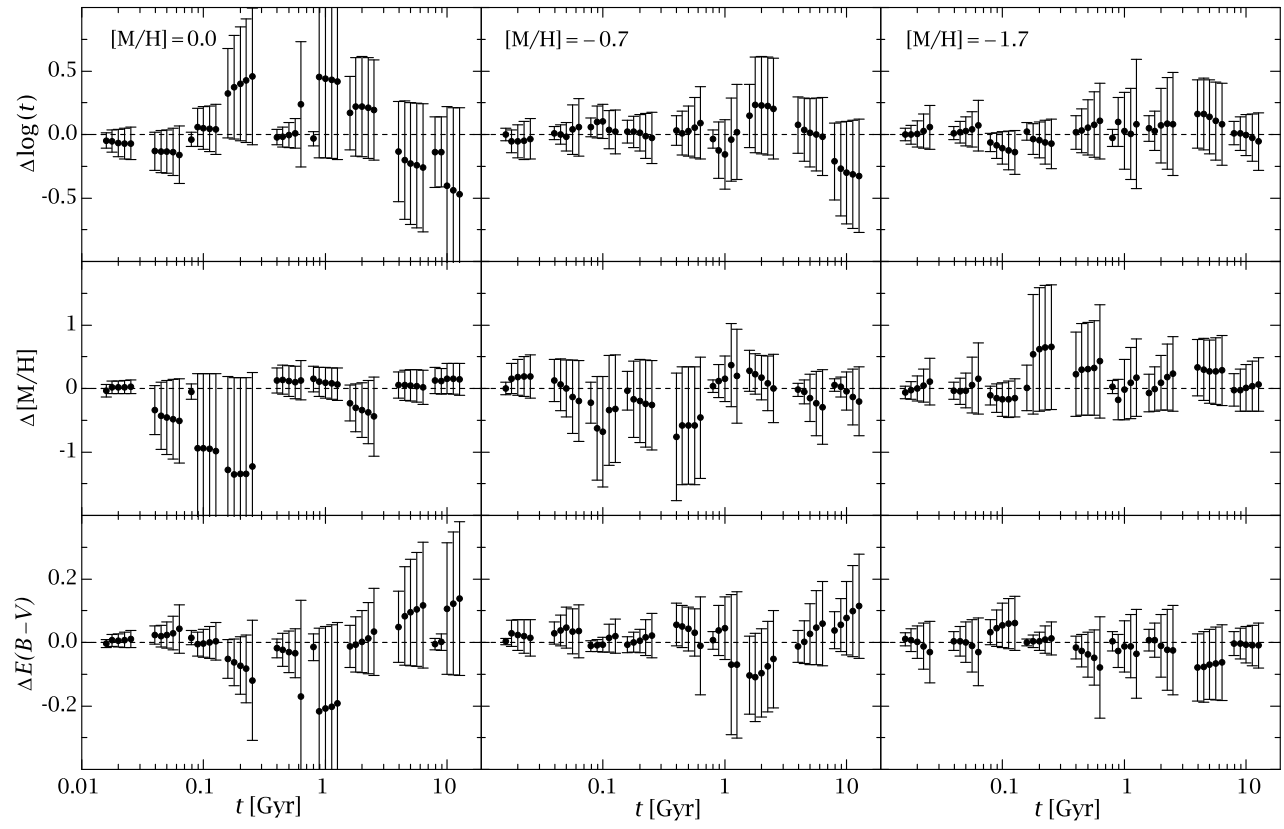


Fig. 2. The same as in Figure 1, but for the case of color excess $E_{B-V} = 1.0$.

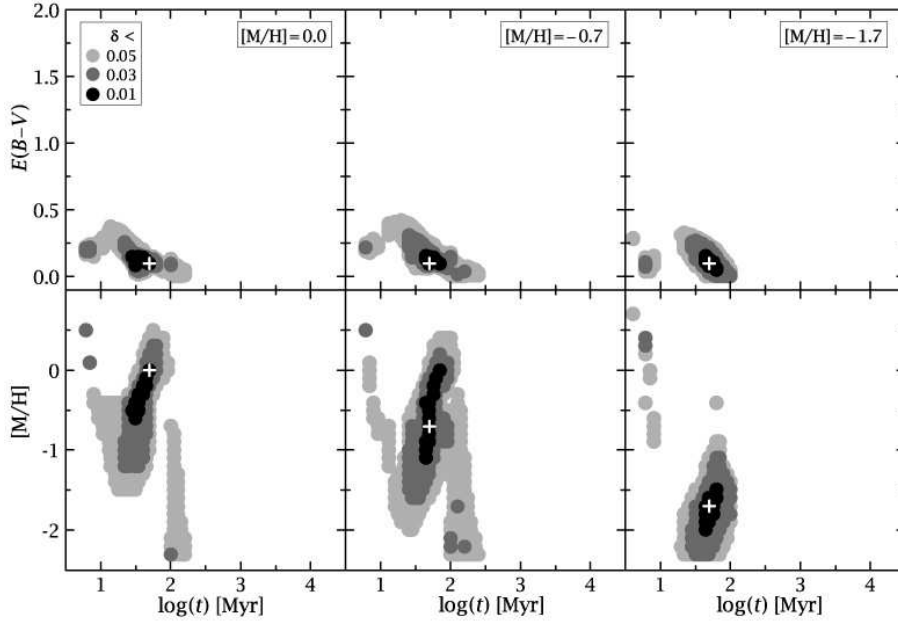


Fig. 3. Parameter quantification maps of the test star clusters of age $t = 50$ Myr, color excess $E_{B-V} = 0.1$ and metallicity $[M/H] = 0.0, -0.7, -1.7$ (left, middle and right panels). True parameter values are marked with a white ‘plus’ symbol. Gray levels correspond to a quantification criterion of $\delta \leq 0.01, 0.03, 0.05$ mag.

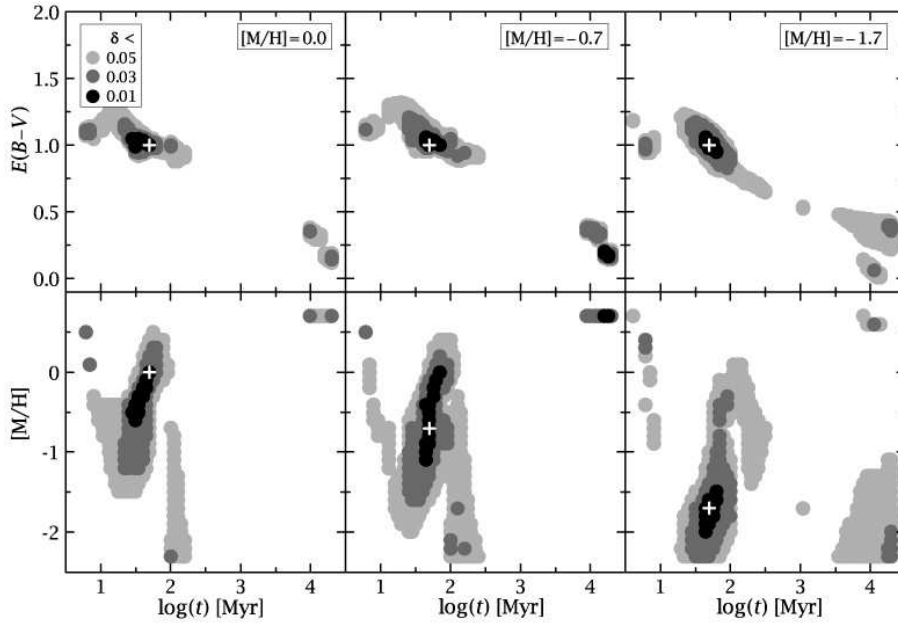


Fig. 4. The same as in Figure 3, but for the case of color excess $E_{B-V} = 1.0$.

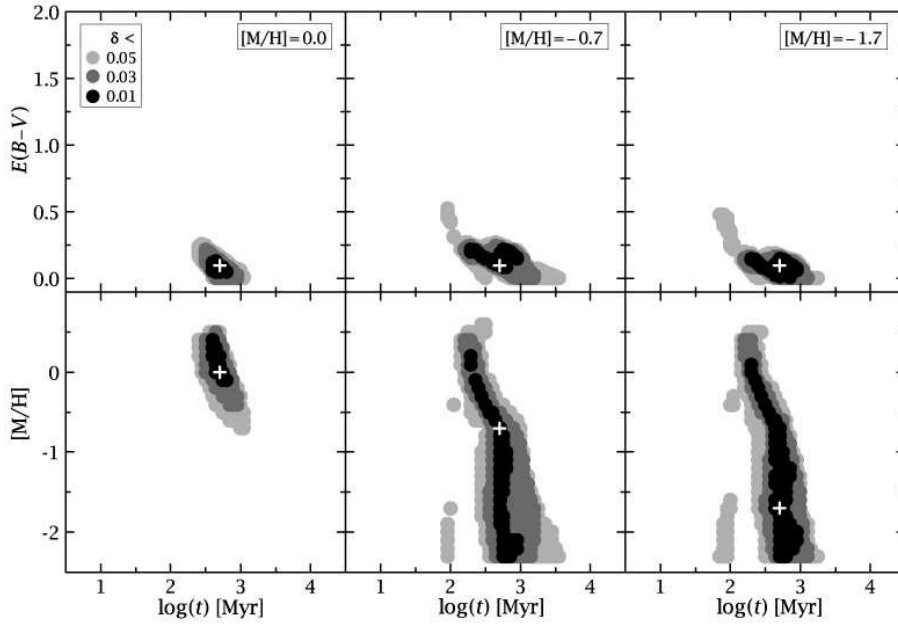


Fig. 5. The same as in Figure 3, but for the case of age $t = 500$ Myr.

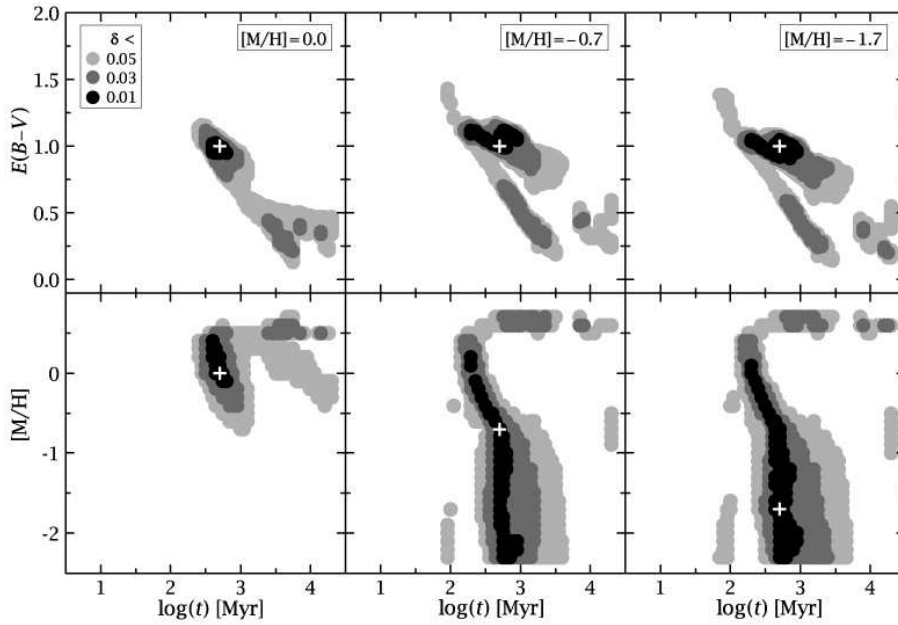


Fig. 6. The same as in Figure 4, but for the case of age $t = 500$ Myr.

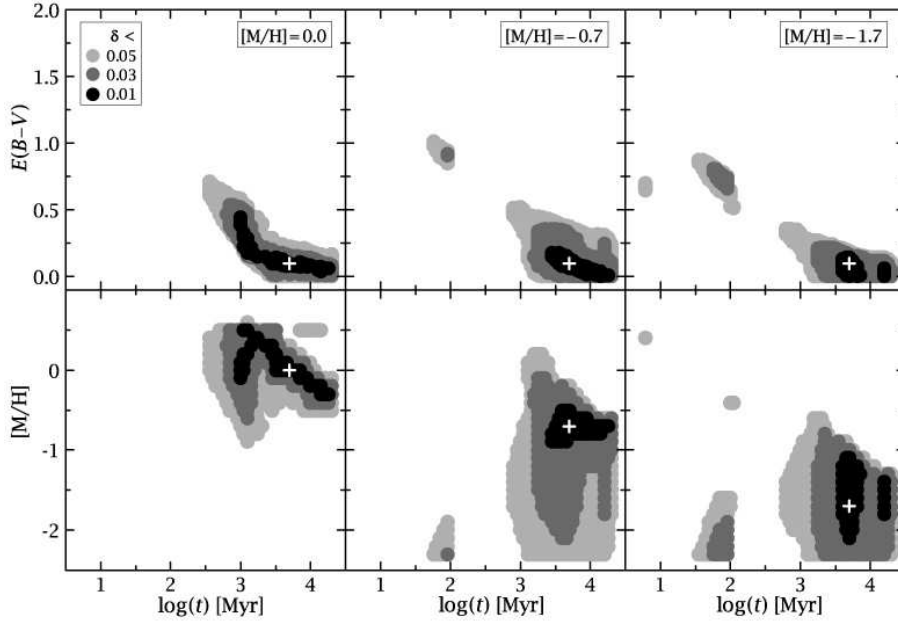


Fig. 7. The same as in Figure 3, but for the case of age $t = 5$ Gyr.

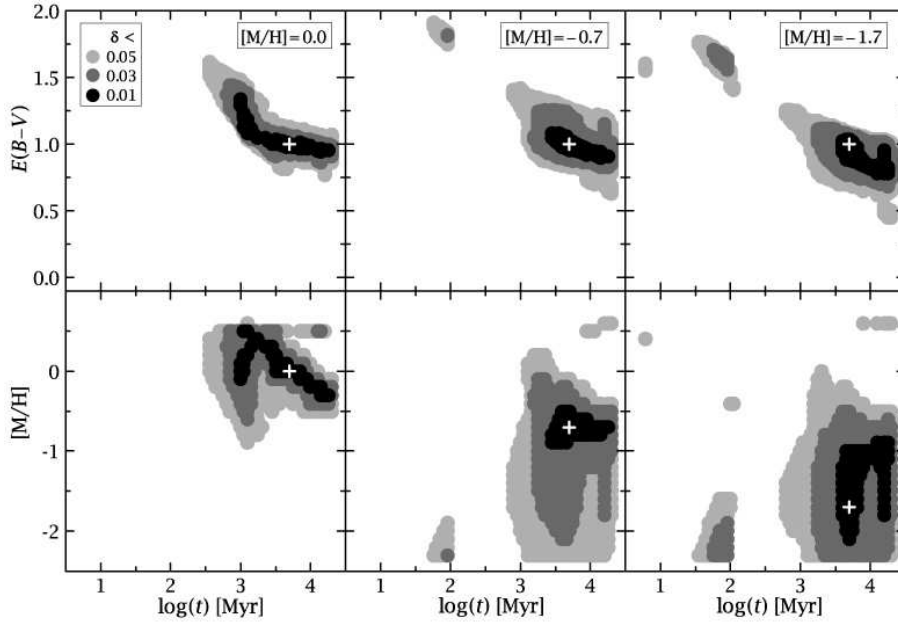


Fig. 8. The same as in Figure 4, but for the case of age $t = 5$ Gyr.

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